SLOPE STABILITY ANALYSIS USING NUMERICAL MODELLING

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF TECHNOLOGY
IN MINING ENGINERING

BY

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DEPARTMENT OF MINING ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA - 769008

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National Institute of Technology, Rourkela

CERTIFICATE

This is to certify that the thesis entitled “Slope Stability analysis using numerical modelling” submitted by Sandeep Suman (Roll No. 111MN0406) in partial fulfillment of the requirements for the award of Bachelor of Technology degree in Mining Engineering at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in this thesis has not formed the basis for the award of any Degree or Diploma or similar title of any University or Institution.

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ABSTRACT

Stability analysis of slopes is a very important component of various opencast mining projects throughout the life cycle of the project. A failure of slope in the area being worked in a mine can lead to some severe social, economic as well as a great safety catastrophe. The basic failure conditions are very diverse & complicated. These failure mechanisms are greatly dependent on local geology, which are pretty unique to a specific location of the rock mass. In the recent years too, the method of designing slopes are completely based upon the field knowledge. Better approach can be made through safe designing of slopes.

The aim of the project is to carry out numerical modelling for slopes having various dimensions and different rock properties. The numerical modelling is carried out using FLAC SLOPE for finding out the factor of safety. The parameters are varied for each slope and the factor of safety calculated for each step. These values are correlated with the bench parameters to find out how the factor of safety changes with changing parameters.

KEYWORDS

FLAC SLOPE, Slope stability, angle of internal friction, cohesion, Factor of safety.

Chapter 1

INTRODUCTION

1.1 OVERVIEW

Analysis of slope stability is an essential part of any opencast mining operation during the full life of the project. In Indian mining scenario, slope design rules are not yet framed for different types of mining practices, and there is an increasing need to develop strategies to maintain safety while increasing production. Still now, many of the designing methods are mostly based on field knowledge and rules of thumb followed by critical engineering judgment. In last few decades, the concept of slope stability analysis have developed under the field of rock engineering mainly to address the difficulties in designing and stability of excavated slopes.

In India, the number of functional opencast mines is on a continuous increase as compared to underground mines, the reason being higher productivity, low gestation period, and quick rate of investment. But the operation of opencast mines attracts a lot of environmental concerns such as solid waste management, land degradation and socio-economic problems. Moreover, a large number of opencast mines, whether large or small, are now a days trying to reach to deeper mining depths. As a result, analysis of stability of working slopes and ultimate pit slope design is becoming a major concern. Slope failure causes a loss in production, increased stripping cost for recovery and handling of resulting failed material, need for dewatering the pits and sometimes leading to mine abandonment or premature closure.

Maintaining pit slope angles that are as steep as possible is of great importance to the reduction of stripping cost, which will have direct consequences on the cost of the mining operations. Design of the final pit limit is not only governed by the ore grade distribution and the production costs, but on the overall rock mass strength and stability as well. The potential for failure must be assessed for every possible mining plans and it should be integrated into the design of the ultimate pit.

In the view of the above, there is a strong need for good and proper practices in slope design and management so that the suitable corrective actions can be taken to minimize any type of slope failure beforehand.

1.2 OBJECTIVES

The primary objectives of this project are as following:

- Understanding the different types of slope failures.
- Understanding the concept of "Factor of Safety".
- Finding relations between different parameters and Factor of Safety.

Although FLAC/Slope is being used here, other software which can be used for numerical analysis are:

- FLAC/Slope
- OASYS
- GALENA
- UDEC
- ROCFALL
- SLIDE
- SLOPE/W
- CLARA-W
- DIPS
- PFC2D/3D
- SVOFFICE
- GEO-STUDIO
- FLAC 3D
- ELFEN
- 3DEC

1.3 PROJECT METHODOLOGY

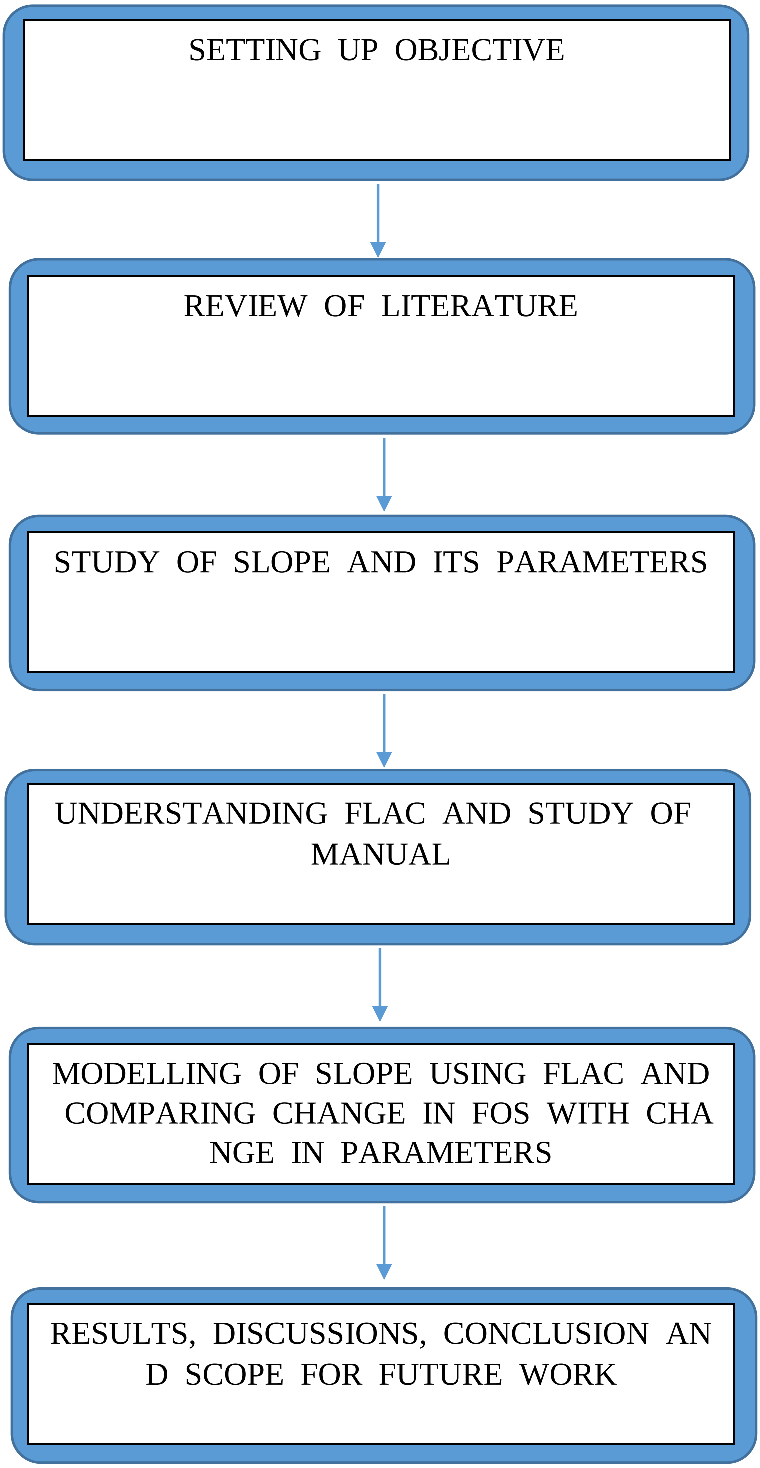


Fig. 1.1 Project Methodology

1.4 OUTLINE OF REPORT

Taking after the introduction chapter, in Chapter 2, a broad portrayal of financial aspects of open pit mining, slope stability, failure mechanisms and failure modes, the slope stability calculation and the different method of analysis are discussed.

“Following that, in Chapter 3, numerical modelling using FLAC/Slope is described, beginning with FLAC’s overview and followed by summary of features and then analysis procedures. The models generated using FLAC are displayed in Chapter 4 and Chapter 5 contains the result, conclusion and the scope for further work.

Chapter 2
LITERATURE REVIEW

2.1 Introduction to open pit slopes

If the mineral deposits are mined from the surface and downward, then the process is called open pit mining. During the process, slopes are formed due to the downward direction of pit. It is not possible all the time to maintain vertical slopes which are stable enough or pit walls which are high enough even in very hard and strong rock. Consequently, pit slopes must be inclined at some angle. The angle of this inclination must be sufficient so that there is no failure in the rock. This angle is thus governed by the local geological factor at any mine and it gives an upper bound to the overall slope angle. But the actual slope angle used in mines may be lower than this and it depends upon:

i. Presence of haulage roads or ramps for transportation.
ii. Possible damage due to blasting.
iii. Grade of ore
iv. Economic constraints

Following figure shows the different parameters used for an opencast mines.

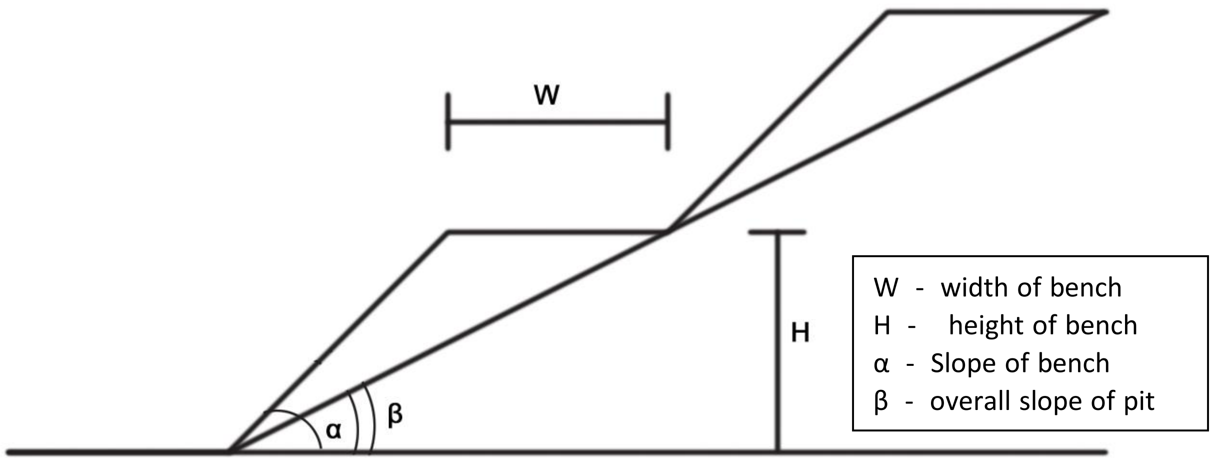


Fig. 2.1 Open pit slope parameters

2.2 Slope Stability

It is one of the greatest problem which any open cast mine encounters. Scale of this problem is divided in:

- Gross stability problem: It refers to the overall problem of stability of major parts of slope due to large shear failure and it generally occurs in deeply weathered rock.
- Local stability problem: It refers to problem which is much lower in scale and it generally doesn't affect more than a couple of benches at one time. It mainly occurs due to shear plane joints or slope erosion due to surface drainage.

Knowing the different failures, the factors affecting them and slope stability techniques is vital to study the different type and scale of failure. Further discussion is based on these parameters.

2.3 Factors affecting Slope Stability

Following factors affect slope stability:

- Slope Geometry
- Geology and geological structure
- Ground water
- Lithology
- Dynamic forces
- Method of mining and equipment used
- Angle of internal friction
- Cohesion

2.3.1 Slope Geometry

Height, overall slope angle and area of failure surface are the elementary geometrical slope design parameters. Slope stability decreases sharply if the height of slope increases. The chances of development of failure to the rear of the crest increases on increasing the overall slope angle and it has to be considered so that any kind of ground deformation can be avoided at the mine peripheral area. Under normal circumstances, an overall slope angle of 45° is considered safe by the DGMS. The curvature of the slope also has intense effect on the instability. Convex section of slopes should be avoided in slope design. Higher and steeper the slope, lower is the stability.

2.3.2 Geological Structure

The main geological structure affecting the stability of the slopes in any open cast mines are:

1. Amount and direction of the dip
2. Intra-formational shear zones
3. Joints and discontinuities
    a. Reduce shear strength
    b. Change permeability
    c. Act as sub-surface drain and plains of failure
4. Faults
    a. Weathering and alteration along the faults
    b. Act as ground water conduits
    c. Provides a probable plane of failure

Instability can occur if strata dips in the excavations. Faults provide a release plane which is either lateral or rear of very low strength and hence the strata is highly disturbed. If some kind of clay or soil band comes in between two rock bands, the stability is highly hindered. Bedding planes and joints also provides surface of weakness. Slope stability also depends on the available shear strength along the surface, their orientation in relation to the slope and water pressure action on the surface. The shear strength that can be mobilized along joint surface depending on the functional properties of the surface and the effective stress which are transmitted normal to the surface. Joints can create a situation where a combination of joint sets provides a cross over surface.

2.3.3 Lithology

The rock materials forming a pit slope determines the rock mass strength modified by discontinuities, folding, faulting, past workings and weathering. Low rock mass strength is characterized by circular; ravelling and rock fall instability like the formation of slope in massive sandstone restrict stability. Pit slopes having alluvium or weathered rocks at the surface have low shearing strength and the strength gets further reduced if water seepage takes place through them. These types of slopes must be flatter.

2.3.4 Ground water

The presence of ground water causes following altercations is the strata:

- It alters the friction and cohesion parameters.
- It reduces the normal effective stress

It can cause increase in up thrust and driving forces and has a highly adverse effect on the stability of slopes. Physical as well as chemical effect of water in joints can alter friction and cohesion of discontinuity surface. Physical effect reduces the shearing resistance along a plane of failure by providing uplift on the joints and reducing the frictional resistance and hence reducing the effective normal stress.

2.3.5 Mining method and equipment

Generally, following 4 methods are used for advancement in open cast mines:

- Strike cut-advancing down the dip
- Strike cut-advancing up the dip
- Dip cut-along the strike
- Open pit working

Using the method of dip cuts with advance on the strike direction reduces the length and time interval that a face is exposed during the excavation process. Dip cuts with high angle to strike should be used to decrease the strata dip in the excavation and provides the most stable method of working with low production. Open cast method are applied in steeply dipping seams, due to the large slope height, are more susceptible to large slab or buckling failure. The mining equipment which are installed on the benches of an open pit mine increases the surcharge load which maximise the force which tends to slope failure. In the case of overburden mainly circular failure occurs.

2.3.6 Dynamic forces

Shear stress is increased due to the vibration caused by blasting process, it maximise the dynamic acceleration of material which in turn causes instability in the slope plane. This accelerates the ground movement results in fracturing of rocks.

Due to the blasting process bench face angles also increases. The effects of poor blasting techniques incurs bench instability. Due to blast damage and back break, these factors also affect the failure in rock mass i.e. the bench face angle, vibrations from blasting. For small scale slopes, many smooth blasting techniques have been adopted to reduce these consequences. In case of larger slopes, blasting has less adverse effects because of back break and blast damage of benches on the stable overall slope angle. The high frequency waves produced due to the blasting process prohibit in the displacement process of large rock masses. Blasting-induced failures are thus a small problem for large scale slopes. Seismic events, i.e., low frequency vibrations, are more prone to large scale slope failures in mountain region.

Together with all these causes external loading can also plays an important role when they are present as in case of surcharge due to dumps on the crest of the benches. In high altitude areas, freezing of water on slope faces can results in the build-up of ground water pressure behind the face which again adds up to instability of the slope.

2.3.7 Angle of internal friction

It is the angle between the normal force and the resultant force when the failure just occurs due to shearing stress. The measure of the material able to withstand any amount of shear stress. Factors are responsible for particle roundness, particle size and amount of quartz content in the soil. More angle of internal friction infers that slope will be higher.

2.3.8 Cohesion

The property of rock that measures to resists being deformed or broken by forces. It is also caused by electrostatic forces in over associated clay or generally by negative capillary pressure and pore pressure due to loading process. Slopes having less cohesion force is less in stable. Factors affecting cohesive force are:

a. Friction
b. Stickiness of particles
c. Cementation of grains by calcite or silica
d. Man-made reinforcement
e. Water content
f. Repeated expansion or contraction due to wetting and drying.
g. Undercutting in slopes

h. Vibrations due to earthquake or blasting

2.4 Types of slope failure

Following are the different types of failure that a slope can undergo:

- Planar failure
- Wedge failure
- Circular failure
- Toppling failure
- Two block failure

2.4.1 Planar failure

The planar failure occurs when a discontinuity striking approximately parallel to the slope of the bench and dipping at a lower angle intersects the slope of the bench, allowing the material above the discontinuity to slide. Variation in the process can arise if the sliding plane is a combination of joint sets developing a straight path.

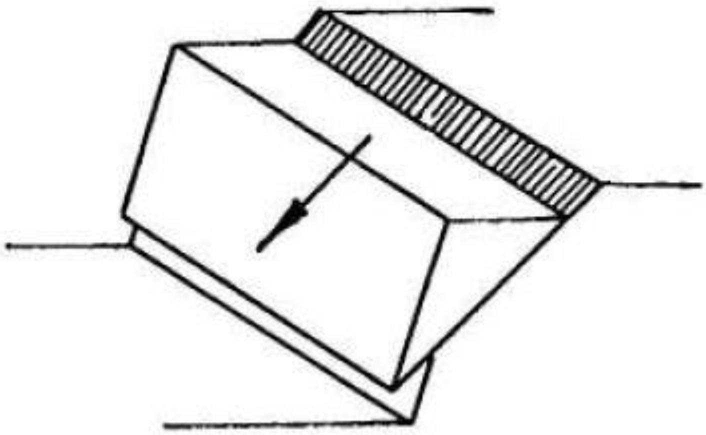


Fig. 2.2 Planar failure

Analysis of a planar failure comprises study of geometry of the slope and following two cases are considered:

a) Slope having tension crack in the upper face

b) Slope with tension crack in slope face.

While the upper surface is horizontal, transition from one condition to another follows when tension crack coincides with slope crest. That is when

$$\frac{Z}{H} = (1 - \cot\psi_f \tan\psi_p)$$

Z – Depth of tension crack
H – slope height
ψ_f – slope angle
ψ_p – dip of sliding plane

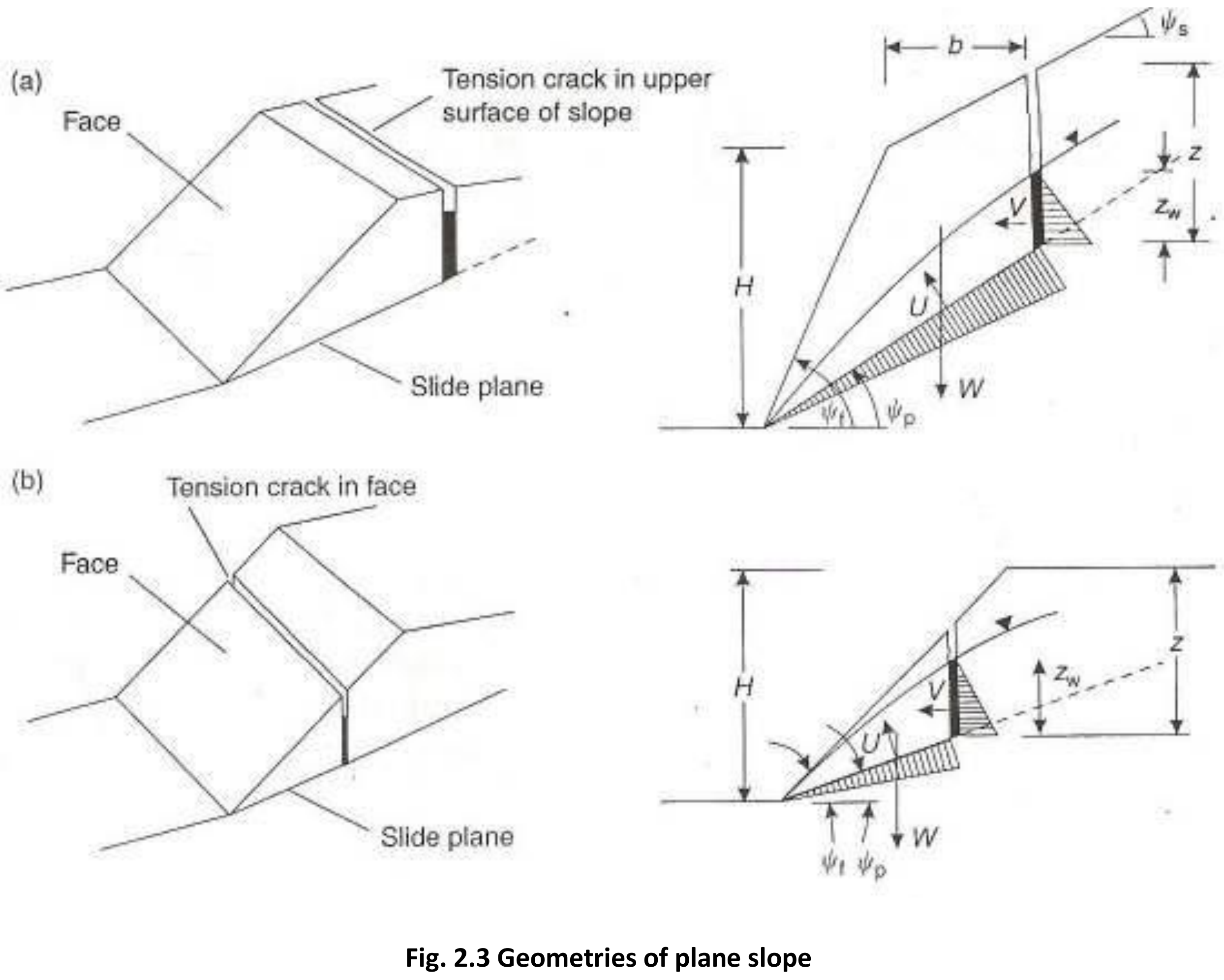


Fig. 2.3 Geometries of plane slope failure

For the analysis, following assumptions are necessary:

a) Both tension crack and sliding surface of a bench strikes parallel to the face.

b) When the tension crack is vertical and filled with water to a depth 'z_w'.

c) Water enters the sliding surface along the base of the tension cracks and percolates along the sliding surface, escaping at atmospheric pressure where the sliding surface daylight in the slope faces.

d) The forces 'W' (weight of sliding block), 'U' (uplift force due to water pressure on the sliding surface) and 'V' (force due to water pressure in the tension crack) all acts through the centroid of the sliding mass.

e) The shear strength of the sliding surface is defined by cohesion 'c' and the friction angle 'φ ' that are related by the equation

$$\tau = c + \sigma \tan\phi$$

f) A wedge of unit thickness is considered and it is assumed that the release surfaces are present so that there is no resistance to the sliding at the lateral boundaries of the failure.

Calculation of factor of safety

The factor of safety of the plane failure is the ratio of the forces acting to keep the failure mass in place (the cohesion times the area of the failure surface plus the frictional shear strength determined using the effective normal stress on the failure plane) to the forces attempting to drive the failure mass down; failure surface (the sum of the component of the weight, water forces, and all other external forces acting along the failure surface). It is calculated by resolving all forces acting on the on the potential failure mass in to directions parallel and normal to the potential failure surface. The general factor of safety which results is:

$$FS = \frac{\text{Resisting force}}{\text{Driving force}}$$

$$FS = \frac{cA + \sum N \tan\phi}{\sum S}$$

Where 'c' is cohesion and 'A' is the area of sliding plane.

The factor of safety for slope configuration in the given figure is:

$$FS = \frac{cA + (W\cos\psi_p - U - V\sin\psi_p)\tan\varphi}{W\sin\psi_p + V\cos\psi_p}$$

Where 'A' is given by

$$A = (H + b\tan\psi_s - z)\operatorname{cosec}\psi_p$$

The slope height 'H', the tension crack depth is 'z' and is located a distance 'b' behind the slope crest. The dip above the crest is 'ψ_s'. When the depth of water in the tension crack is 'z_w', the water forces acting on the sliding plane 'U' and in the tension crack 'V' are given by:

$$U = \frac{1}{2}\gamma_w z_w (H + b\tan\psi_s - z)\operatorname{cosec}\psi_p$$

$$V = \frac{1}{2}\gamma_w z_w^{\ 2}$$

Where 'γ_w' is the unit weight of water.

The weight of the sliding block for geometries shown in figure is given by:

$$W=\gamma_r[(1-\cot\psi_f\tan\psi_p)(bH+\frac{1}{2}H^2\cot\psi_f)+\frac{1}{2}b^2(\tan\psi_s-\tan\psi_p)]$$

And for the tension crack in the slope face

$$W=\frac{1}{2}\gamma_r H^2[(1-\frac{z}{H})^2\cot\psi_p\times(\cot\psi_p\tan\psi_f-1)]$$

Where 'γ_r' is the unit weight of the rock.

2.4.2 Wedge failure

The three dimensional wedge failures occur when two discontinuities intersects in such a way that the wedge of material, formed above the discontinuities, can slide out in a direction parallel to the line of intersection of the two discontinuities. It is particularly common in the individual bench scale but can also provide the failure mechanism for a large slope where structures are very continuous and extensive.

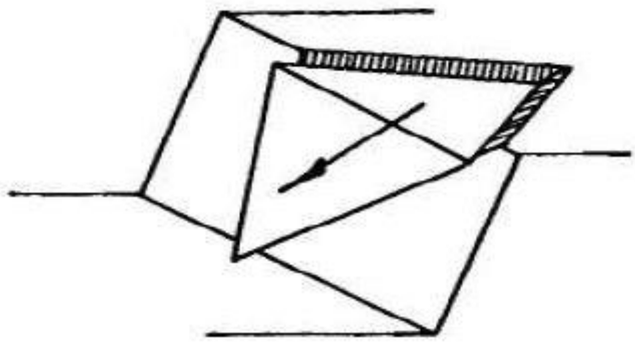


Fig. 2.4 Wedge failure

When two discontinuities strike obliquely across the slope face and their line of intersection 'daylights' in the slope, the wedge of the rock resting over these discontinuities will slide down along the line of intersection provided the inclination of these line is significantly greater than the angle of friction and the shearing component of the plane of the discontinuities is less than the total downward force. The total downward force is the downward component of the weight of the wedge and the external forces (surcharges) acting over the wedge.

The wedge failure analysis is based on satisfying the equilibrium conditions of the wedge. If 'w' be the weight of the wedge, the vector 'w' can be divided into two components in the parallel and normal directions to the joint intersection,

$$N = w \cos \theta, P = w \sin \theta$$

The vector 'N' in the Fig. 2.6 is divided into two components 'N1' and 'N2', normal to the joint set surfaces 1 and 2, respectively as follows:

In Fig. 2.5 the equilibrium conditions in the directions x and y are as follows:

$$N_{1x} = N_2x, N_{1y} + N_{2y} = N$$

$$N_{1x} = N_1 \sin \alpha_1, N_{2x} = N2 \sin \alpha_2$$

$$N_{1y} = N_1 \cos \alpha_1, N_{2y} = N2 \cos \alpha_2$$

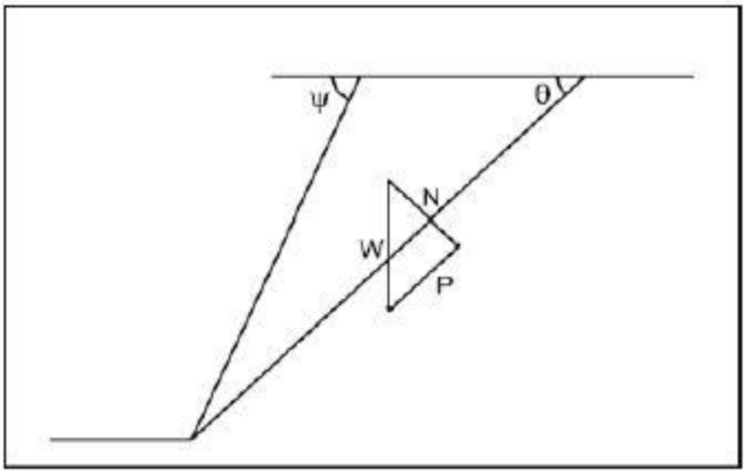


Fig. 2.5 Conditions of effective forces in the wedge failure analysis

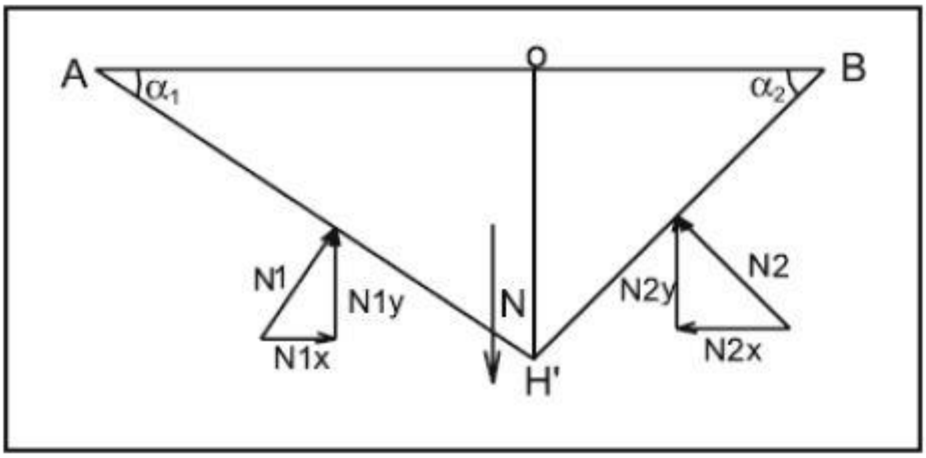


Fig. 2.6 Plane normal to the intersection of joint sets 1 and 2

The forces ‘N1’ and ‘N2’ can be obtained from the Equations. (12), (13), and (14) as follows:

$$\begin{cases} \mathbf{N_1 sin\alpha_1 = N_2 sin\alpha_2} \\ \mathbf{N_1 cos\alpha_1 + N_2 cos\alpha_2 = N = W cos\theta} \end{cases}$$

Where,

$$\mathbf{N_1 = \frac{N sin\alpha_2}{sin(\alpha_1+\alpha_2)}},\ \mathbf{N_2 = \frac{N sin\alpha_1}{sin(\alpha_1+\alpha_2)}}$$

Calculation of the angles α_1 and α_2

In Fig. 2.7 the line CC’ is the intersection line of two joint surfaces 1 and 2. The segment OH is drawn vertically in the normal plane passing through the line of intersection CC’. Fig. 2.6 is drawn in the three-dimensional view as the triangle ABH’. From the point O the segment OH’ normal to the intersection is drawn. The plane ABH’ is the plane normal to the intersection CC’ at point H’. From the points H and A on plane 1, two lines are drawn so that the first one is parallel to the strike and the second one is in the direction of dip line.

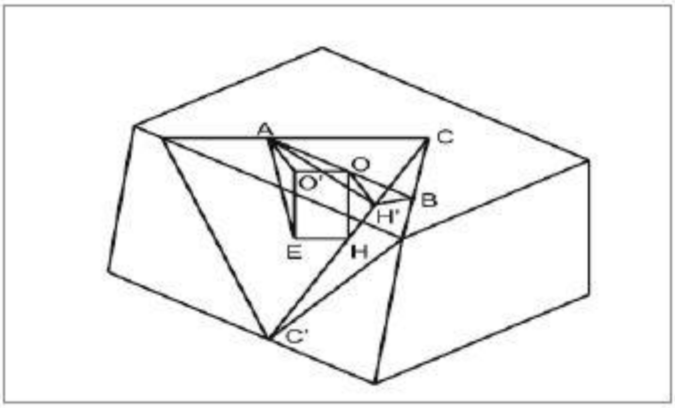


Fig. 2.7 The geometry of the sliding wedge

These two lines intersect at point E. EO' is drawn parallel and with the same size as HO. The quadrilateral OO'EH is rectangle. Using the geometric and trigonometric relationships in the triangles H'OA, OO'A, and O'AE, the angles α_1 and α_2 are obtained from the following equation. $\cos\theta \cos \gamma_1 \tan d_1 = \frac{H'O}{HO} * \frac{AO'}{AO} * \frac{EO'}{AO'} = \frac{HO'}{AO} = \tan\alpha_1$

It can be shown in the same way that **$\tan\alpha_2 = \cos\theta \cos\gamma_2 \tan d_2$** where HO = EO', ∠EAO' = ∠d_1, ∠OAH\` = ∠α1, ∠OBH\` = ∠α2, ∠HOH\` = ∠θ, and ∠OAO\` = ∠γ1 in which 'd1' and 'd2' are the slope angles of the joint set 1 and 2, respectively. The angles 'γ1' and 'γ2' are the angle between the dip directions of joint sets 1 and 2 and the strike of the plane normal to intersection line, respectively.

The factor of safety can be calculated from the equation given below:

$$FS = \frac{T_1 + T_2}{w \sin\theta}$$

Where,

$$T_1 = N_1 \tan(\phi_{j1} + i_1)(1-a_1) + C_{j1}(1-a_1)S_1 + N_1 a_1 \tan\phi_{r1} + C_{r1} a_1 S_1$$

$$T_2 = N_2 \tan(\phi_{j2} + i_1)(1-a_2) + C_{j2}(1-a_2)S_1 + N_2 a_2 \tan\phi_{r2} + C_{r2} a_2 S_2$$

The internal frictions of the intact rock '$Ø_{r1}$' and '$Ø_{r2}$' and the cohesion coefficients of the intact rock 'C_{r1}' and 'C_{r2}' are determined from the triaxial compressive tests and using the Mohr–Coulomb criterion. The correction factor for the effect of intact rock specimen diameter on the cohesion coefficients could also be included. The internal friction angles of the joint sets 1 and 2 surfaces 'φ_{j1}' and 'φ_{j2}' are obtained from the shear tests on the polished rock joint specimens. The irregularity angles 'i_1' and 'i_2' are determined from the direct measurements on the rock outcrops using the stereographic projections of the joint sets 1 and 2.

2.4.3 Circular failure

The pioneering work, in the beginning of the century, in Sweden confirmed that the surface of the failure in spoil dumps or soil slopes resembles the shape of a circular arc. This failure can occurs in soil slopes, the circular method occurs when the joint sets are not very well defined. When the material of the spoil dump slopes are weak such as soil, heavily jointed or broken rock mass, the failure is defined by a single discontinuity surface but will tend to follow a circular path.

The conditions under which circular failure occurs are as follows:

a. When the individual particles of soil or rock mass, comprising the slopes are small as compared to the slope.
b. When the particles are not locked as a result of their shape and tend to behave as soil.

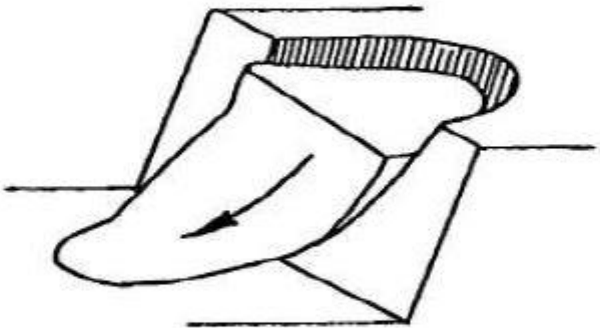


Fig. 2.8 Circular failure

Types of circular failure

Circular failure is generally classified in three types depending on the area that is affected by the failure surface. They are:

a) Slope failure: In this type of failure, the arc of the rupture surface meets the slope above the toe of the slope. This happens when the slope angle is very high and the soil close to the toe possess the high strength.

b) Toe failure: In this type of failure, the arc of the rupture surface meets the slope at the toe.

c) Base failure: In this type of failure, the arc of the failure passes below the toe and in to base of the slope. This happens when the slope angle is low and the soil below the base is softer and more plastic than the soil above the base.

2.4.4 Two block failure

Two block failures are much less common mode of rock slope failure than single block failures such as the planes and the 3D wedge and, consequently, are only briefly considered here. Several methods of solution exist and each may be appropriate at some level of investigation.

2.4.5 Toppling failure

Toppling or overturning has been recognized by several investigators as being a mechanism of rock slope failure and has been postulated as the cause of several failures ranging from small to large ones. It occurs in slopes having near vertical joint sets very often the stability depends on the stability of one or two key blocks. Once they are disturbed the system may collapse or this failure has been postulated as the cause of several failures ranging from small to large size. This type of failure involves rotation of blocks of rocks about some fixed base. This type of failure generally occurred when the hill slopes are very steep.

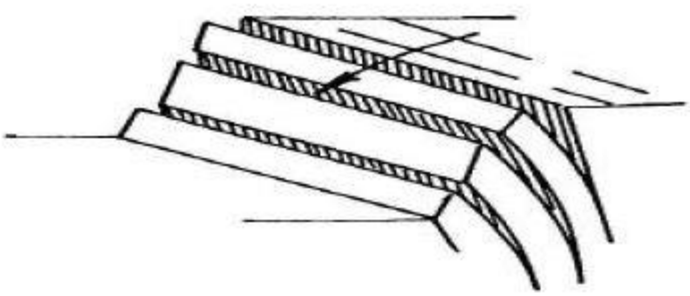


Fig. 2.9 Toppling failure

2.5 Factors to be considered in assessment of stability

2.5.1 Ground Investigation

Before any further examination of an existing slope, or the ground on which a slope is to be built, essential borehole information must be obtained. This information will give details of the strata, moisture content and the standing water level and shear planes. Piezometer tubes are installed into the ground to measure changes in water level over a period of time. Ground investigations also include:-

- In-situ and laboratory,
- Aerial photographs,
- Study of geological maps and memoirs to indicate probable soil conditions
- Visiting and observing the slope

2.5.2 Most Critical Failure Surface

In homogeneous soils relatively unaffected by faults or bedding, deep seated shear failure surfaces tend to form in a circular, rotational manner. The aim is to find the most critical surface using "trial circles".

The method is as follows:

- A series of slip circles of different radii is to be considered but with same centre of rotation. Factor of Safety (FOS) for each of these circles is plotted against radius, and the minimum FOS is found.
- This should be repeated for several circles, each investigated from an array of centres. The simplest way to do this is to form a rectangular grid from the centres.
- Each centre will have a minimum FOS and the overall lowest FOS from all the centre shows that FOS for the whole slope. This assumes that enough circles, with a large spread of radii, and a large grid of centres have been investigated.
- An overall failure surface is found.

Fig. 2.10 & Fig. 2.11 shows variety of slope failure circles analysed at varying radii from a single centre and variation of factor of safety with critical circle radius respectively.

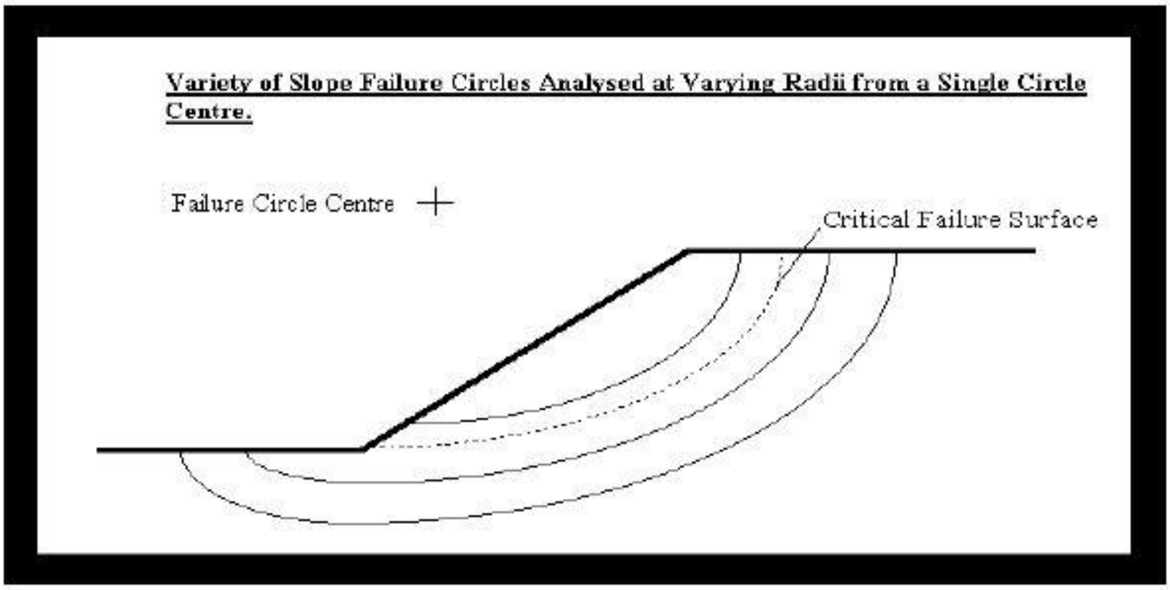


Fig. 2.10 Variety of slope failure circles analysed at varying radii from a single centre

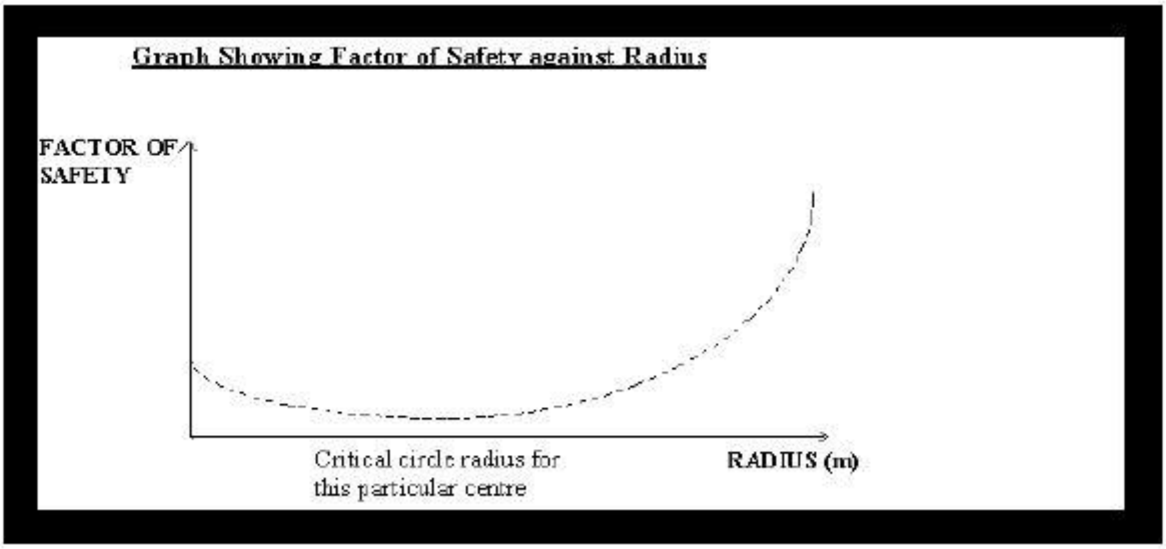
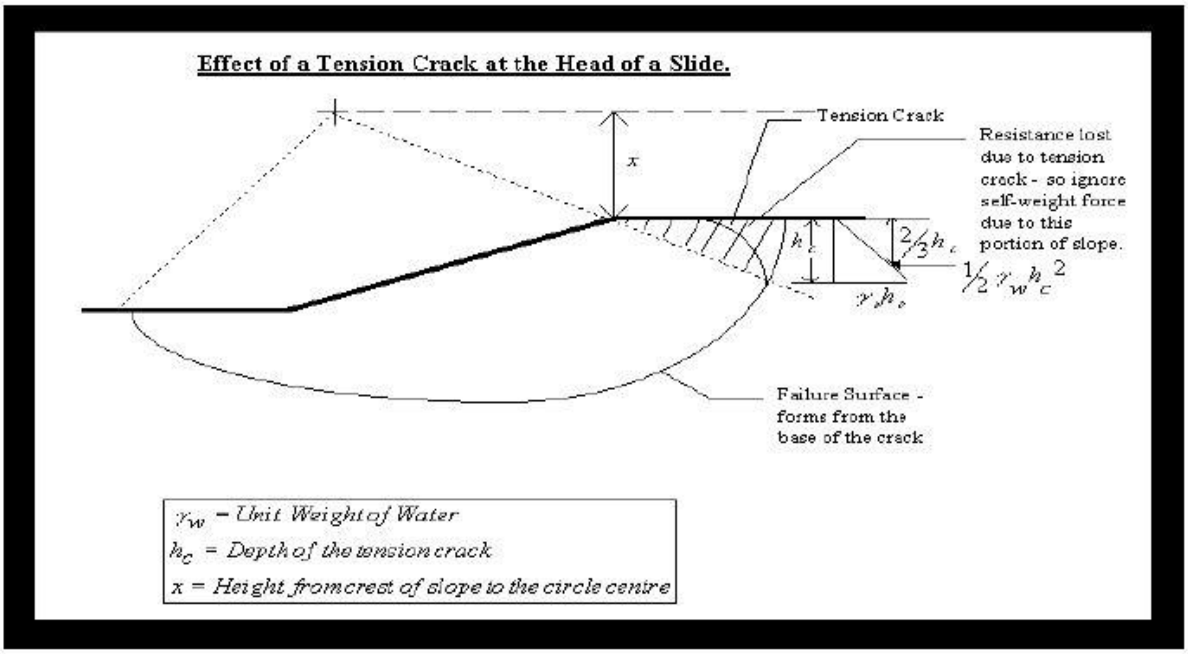


Fig. 2.11 Variation of factor of safety with critical circle radius

2.5.3 Tension cracks

A tension crack at the head of a slide suggests strongly that instability is imminent. Tension cracks are sometimes used in slope stability calculations, and sometimes they are considered to be full of water. If this is the case, then hydrostatic forces develop as shown in Fig. 2.12. Tension cracks are not usually important in stability analysis, but can become so in some special cases. Therefore assume that the cracks don't occur, but take account of them in analysing a slope which has already cracked.

Fig. 2.12 Effect of tension crack at the head of a slide



2.5.4 Submerged Slopes

When an external water load is applied to a slope, the pressure it exerts tends to have a stabilizing effect on the slope. The vertical and horizontal forces due to the water must be taken into account in analysis of the slope. Thus, allowing for the external water forces by using submerged densities in the slope, and by ignoring water externally.

2.5.5 Factor of Safety

The FOS is chosen as a ratio of the available shear strength to that required to keep the slope stable.

Table 2.1 Guidelines for slopes

FACTOR OF SAFETY	DETAILS OF SLOPE
<1.0	Unsafe
1.0 1.25	Questionable Safety
1.25 - 1.4	Satisfactory for routine cuts and fills Questionable for dams, or where failure would be catastrophic
>1.4	Satisfactory for dams

For highly unlikely loading conditions, factors of safety can be as low as 1.2-1.25, even for dams. E.g. situations based on seismic effects, or where there is rapid drawdown of the water level in a reservoir.

2.5.6 Progressive failure

This is the term describing the condition when different parts of a failure surface reach failure at different times. This often occurs if a potential failure surface passes through a foundation material which is fissured or has joints or pre-existing failure surfaces. Where these fissures occur there will be large strain values, so the peak shear strength is reached before other places.

2.5.7 Pre-existing failure surface

If the foundation on which a slope sits contains pre-existing failure surfaces, there is a large possibility that progressive failure will take place if another failure surface were to cut through them. The way to deal with this situation is to assume that sufficient movement has previously taken place for the ultimate state to develop in the soil and then using the ultimate state parameters. If failure has not taken place, then a decision has to be made on which parameters to be used.

Chapter 3
INTRODUCTION TO FLAC

3.1 Introduction

Many rock slope stability problems involve complexities relating to geometry, material anisotropy, non-linear behaviour, in situ stresses and the presence of several coupled processes (e.g. pore pressures, seismic loading, etc.). Advances in computing power and the availability of relatively inexpensive commercial numerical modelling codes means that the simulation of potential rock slope failure mechanisms could, and in many cases should, form a standard component of a rock slope investigation.

Numerical methods of analysis used for rock slope stability may be conveniently divided into three approaches: continuum, discontinuum and hybrid modelling. Table 2 provides a summary of existing numerical techniques.

Analysis method	Critical Input Parameters	Advantages	Limitations
Continuum Modelling (e.g. Finite Element, Finite Difference Method)	Representative slope geometry; constitutive criteria (e.g. elastic, elasto-plastic, creep etc.); groundwater characteristics; shear strength of surfaces; in situ stress state.	Allows for material deformation and failure. Can model complex behaviour and mechanisms. Capability of 3-D modelling. Can model effects of groundwater and pore pressures. Able to assess effects of parameter variations on instability. Recent advances in computing hardware allow complex models to be solved on PC's with reasonable run times. Can incorporate creep deformation. Can incorporate dynamic analysis.	Users must be well trained, experienced and observe good modelling practice. Need to be aware of model/software limitations (e.g. boundary effects, mesh aspect ratios, symmetry, hardware memory restrictions). Availability of input data generally poor. Required input parameters not routinely measured. Inability to model effects of highly jointed - 30 - analysis. rock. Can be difficult to perform sensitivity analysis due to run time
Discontinuum Modelling (e.g. Distinct	Representative slope and discontinuity geometry; intact constitutive criteria;	Allows for block deformation and movement of blocks relative to each other. Can	As above, experienced user required to observe

Element, Discrete Element Method)	discontinuity stiffness and shear strength; groundwater characteristics; in situ stress state.	model complex behaviour and mechanisms (combined material and discontinuity behaviour coupled with hydromechanical and dynamic analysis). Able to assess effects of parameter variations on instability.	good modelling practice. General limitations similar to those listed above. Need to be aware of scale effects. Need to simulate representative discontinuity geometry (spacing, persistence, etc.). Limited data on joint properties available.
Hybrid/Coupled Modelling	Combination of input parameters listed above for stand-alone models.	Coupled finiteelement/ distinct element models able to simulate intact fracture propagation and fragmentation of jointed and bedded media.	Complex problems require high memory capacity. Comparatively little practical experience in use. Requires ongoing calibration and constraints.

Table 3.1 Numerical method for analysis

3.1.1 Continuum modelling

Continuum modelling is best suited for the analysis of slopes that are comprised of massive, intact rock, weak rocks, and soil-like or heavily fractured rock masses. Most continuum codes incorporate a facility for including discrete fractures such as faults and bedding planes but are inappropriate for the analysis of blocky mediums. The continuum approaches used in rock slope stability include the finite-difference and finite-element methods. In recent years the vast majority of published continuum rock slope analyses have used the 2-D finite-difference code, FLAC. This code allows a wide choice of constitutive models to characterize the rock mass and incorporates time dependent behaviour, coupled hydro-mechanical and dynamic modelling. Two-dimensional continuum codes assume plane strain conditions, which are frequently not valid in inhomogeneous rock slopes with varying structure, lithology and topography. The recent advent of 3-D continuum codes such as FLAC3D and VISAGE enables the engineer to undertake 3-D analyses of rock slopes on a desktop computer. Although 2-D and 3-D continuum codes are extremely useful in characterizing rock slope failure mechanisms it is the responsibility of the engineer to verify whether they are representative of the rock mass under consideration. Where a rock slope comprises multiple joint sets, which control the mechanism of failure, then a discontinuum modelling approach may be considered more appropriate.

3.1.2 Discontinuum modelling

Discontinuum methods treat the rock slope as a discontinuous rock mass by considering it as an assemblage of rigid or deformable blocks. The analysis includes sliding along and opening/closure of rock discontinuities controlled principally by the joint normal and joint shear stiffness. Discontinuum modelling constitutes the most commonly applied numerical approach to rock slope analysis, the most popular method being the distinct-element method. Distinctelement codes such as UDEC use a force-displacement law specifying interaction between the deformable joint bounded blocks and Newton's second law of motion, providing displacements induced within the rock slope.

UDEC is particularly well suited to problems involving jointed media and has been used extensively in the investigation of both landslides and surface mine slopes. The influence of external factors such as underground mining, earthquakes and groundwater pressure on block sliding and deformation can also be simulated.

3.1.3 Hybrid Techniques

Hybrid approaches are increasingly being adopted in rock slope analysis. This may include combined analyses using limit equilibrium stability analysis and finite-element groundwater flow and stress analysis such as adopted in the GEO-SLOPE suite of software. Hybrid numerical models have been used for a considerable time in underground rock engineering including coupled boundary-/finite-element and coupled boundary-/distinct-element solutions. Recent advances include coupled particle flow and finite-difference analyses using FLAC3D and

PFC3D. These hybrid techniques already show significant potential in the investigation of such phenomena as piping slope failures, and the influence of high groundwater pressures on the failure of weak rock slopes. Coupled finite-/distinct-element codes are now available which incorporate adaptive remeshing. These methods use a finite-element mesh to represent either the rock slope or joint bounded block. This is coupled with a discrete -element model able to model deformation involving joints. If the stresses within the rock slope exceed the failure criteria within the finite-element model a crack is initiated. Remeshing allows the propagation of the cracks through the finite-element mesh to be simulated. Hybrid codes with adaptive remeshing routines, such as ELFEN, have been successfully applied to the simulation of intense fracturing associated with surface mine blasting, mineral grinding, retaining wall failure and underground rock caving.

3.2 General Approach of FLAC

The modelling of geo-engineering processes involves special considerations and a design philosophy different from that followed for design with fabricated materials. Analyses and designs for structures and excavations in or on rocks and soils must be achieved with relatively little site-specific data, and an awareness that deformability and strength properties may vary considerably. It is impossible to obtain complete field data at a rock or soil site.

Since the input data necessary for design predictions are limited, a numerical model in geomechanics should be used primarily to understand the dominant mechanisms affecting the behaviour of the system. Once the behaviour of the system is understood, it is then appropriate to develop simple calculations for a design process.

It is possible to use FLAC directly in design if sufficient data, as well as an understanding of material behaviour, are available. The results produced in a FLAC analysis will be accurate when the program is supplied with appropriate data. Modellers should recognize that there is a continuous spectrum of situations.

The model should never be considered as a “black box” that accepts data input at one end and produces a prediction of behaviour at the other. The numerical “sample” must be prepared carefully, and several samples tested, to gain an understanding of the problem. Following steps are recommended to perform a successful numerical experiment:

3.2.1 Define the objectives for the model analysis

The level of detail to be included in a model often depends on the purpose of the analysis. For example, if the objective is to decide between two conflicting mechanisms that are proposed to explain the behaviour of a system, then a crude model may be constructed, provided that it allows the mechanisms to occur. It is tempting to include complexity in a model just because it exists in reality. However, complicating features should be omitted if they are likely to have little influence on the response of the model, or if they are irrelevant to the model’s purpose. Start with a global view and add refinement if necessary.

3.2.2 Create a conceptual picture of the physical system

It is important to have a conceptual picture of the problem to provide an initial estimate of the expected behaviour under the imposed conditions. Several questions should be asked when preparing this picture. For example, is it anticipated that the system could become unstable? Is the predominant mechanical response linear or nonlinear? Are movements expected to be large or small in comparison with the sizes of objects within the problem region? Are there well-defined discontinuities that may affect the behaviour, or does the material behave essentially as a continuum? Is there an influence from groundwater interaction? Is the system bounded by physical structures, or do its boundaries extend to infinity? Is there any geometric symmetry in the physical structure of the system?

These considerations will dictate the gross characteristics of the numerical model, such as the design of the model geometry, the types of material models, the boundary conditions, and the initial equilibrium state for the analysis. They will determine whether a three-dimensional model is required, or if a two-dimensional model can be used to take advantage of geometric conditions in the physical system.

3.2.3 Construct and run simple idealized models

When idealizing a physical system for numerical analysis, it is more efficient to construct and run simple test models first, before building the detailed model. Simple models should be created at the earliest possible stage in a project to generate both data and understanding. The results can provide further insight into the conceptual picture of the system; Step 2 may need to be repeated after simple models are run.

Simple models can reveal shortcomings that can be remedied before any significant effort is invested in the analysis. For example, do the selected material models sufficiently represent the expected behaviour? Are the boundary conditions influencing the model response? The results from the simple models can also help guide the plan for data collection by identifying which parameters have the most influence on the analysis.

3.2.4 Assemble problem specific data

The types of data required for a model analysis include:

- Details of geometry
- Location of geological structure
- Material behaviour
- Initial conditions
- External loading

3.2.5 Prepare a series of detailed model runs

Most often, the numerical analysis will involve a series of computer simulations that include the different mechanisms under investigation and span the range of parameters derived from the assembled database. When preparing a set of model runs for calculation, several aspects, such as those listed below, should be considered:

I. How much time is required to perform each model calculation? It can be difficult to obtain sufficient information to arrive at a useful conclusion if model runtimes are excessive. Consideration should be given to performing parameter variations on multiple computers to shorten the total computation time.

II. The state of the model should be saved at several intermediate stages so that the entire run does not have to be repeated for each parameter variation. For example, if the analysis involves several loading/unloading stages, the user should be able to return to any stage, change a parameter and continue the analysis from that stage.

III. Are there a sufficient number of monitoring locations in the model to provide for a clear interpretation of model results and for comparison with physical data? It is helpful to locate several points in the model at which a record of the change of a parameter (such as displacement) can be monitored during the calculation.

3.2.6 Perform the model calculations

It is best to first make one or two model runs split into separate sections before launching a series of complete runs. The runs should be checked at each stage to ensure that the response is as expected. Once there is assurance that the model is performing correctly, several data files can be linked together to run a complete calculation sequence. At any time during a sequence of runs, it should be possible to interrupt the calculation, view the results, and then continue or modify the model as appropriate.

3.2.7 Present results for interpretation

The final stage of problem solving is the presentation of the results for a clear interpretation of the analysis. This is best accomplished by displaying the results graphically, either directly on the computer screen, or as output to a hardcopy plotting device. The graphical output should be presented in a format that can be directly compared to field measurements and observations. Plots should clearly identify regions of interest from the analysis, such as locations of calculated stress concentrations, or areas of stable movement versus unstable movement in the model. The numeric values of any variable in the model should also be readily available for more detailed interpretation by the modeller.

3.3 Overview

FLAC/Slope is a mini-version of FLAC that is designed specifically to perform factor-of-safety calculations for slope stability analysis. This version is operated entirely from FLAC's graphical interface (the GIIC) which provides for rapid creation of models for soil and/or rock slopes and solution of their stability condition.

FLAC/Slope provides an alternative to traditional "limit equilibrium" programs to determine factor of safety. Limit equilibrium codes use an approximate scheme — typically based on the method of slices — in which a number of assumptions are made (e.g., the location and angle of interslice forces). Several assumed failure surfaces are tested, and the one giving the lowest factor of safety is chosen. Equilibrium is only satisfied on an idealized set of surfaces. In contrast, it provides a full solution of the coupled stress/displacement, equilibrium and constitutive equations. Given a set of properties, the system is determined to be stable or unstable. By automatically performing a series of simulations while changing the strength properties, the factor of safety can be found to correspond to the point of stability, and the critical failure (slip) surface can be located.

FLAC/Slope does take longer to determine a factor of safety than a limit equilibrium program. However, with the advancement of computer processing speeds (e.g., 1 GHz and faster chips), solutions can now be obtained in a reasonable amount of time. This makes FLAC/Slope a practical alternative to a limit equilibrium program, and provides advantages over a limit equilibrium solution:

1. Any failure mode develops naturally, there is no need to specify a range of trial surfaces in advance.
2. No artificial parameters need to be given as input.
3. Multiple failure surfaces evolve naturally, if the conditions give rise to them.
4. Structural interaction is modelled realistically as fully coupled deforming elements, not simply as equivalent forces.
5. The solution consists of mechanisms that are kinematically feasible.

3.4 Analysis Procedure

FLAC/Slope is specifically designed to perform multiple analyses and parametric studies for slope stability projects. The structure of the program allows different models in a project to be easily created, stored and accessed for direct comparison of model results. A FLAC/Slope analysis project is divided into four stages which is described below:

a. **Model Stage**

   Each model in a project is named and listed in a tabbed bar in the Models stage. This deleted from it at any time in the project study. Models can also be restored (loaded) from allows easy access to any model and results in a project. New models can be added to the tabbed bar or previous projects and added to the current project. The slope boundary is also defined for each model at this stage.

b. **Build Stage**

For a specific model, the slope conditions are defined in the Build stage. This includes: changes to the slope geometry, addition of layers, specification of materials and weak plane, application of surface loading, positioning of a water table and installation of reinforcement. Also, spatial regions of the model can be excluded from the factor-of-safety calculation. The build-stage conditions can be added, deleted and modified at any time during this stage.

c. **Solve Stage**

In the Solve stage, the factor of safety is calculated. The resolution of the numerical mesh is selected first (coarse, medium and fine), and then the factor-of-safety calculation is performed. Different strength parameters can be selected for inclusion in the strength reduction approach to calculate the safety factor. By default, the material cohesion and friction angle are used.

d. **Plot Stage**

After the solution is complete, several output selections are available in the Plot stage for displaying the failure surface and recording the results. Model results are available for subsequent access and comparison to other models in the project. All models created within a project, along with their solutions, can be saved, the project files can be easily restored and results viewed at a later time.

Chapter 4
NUMERICAL MODELLING

Parametric studies were conducted through numerical models (FLAC/Slope) to study the effect of cohesion (6000-12000 Pa) and friction angle (20°-30° at the interval of 2°). The dimension of the example slope are as follows.

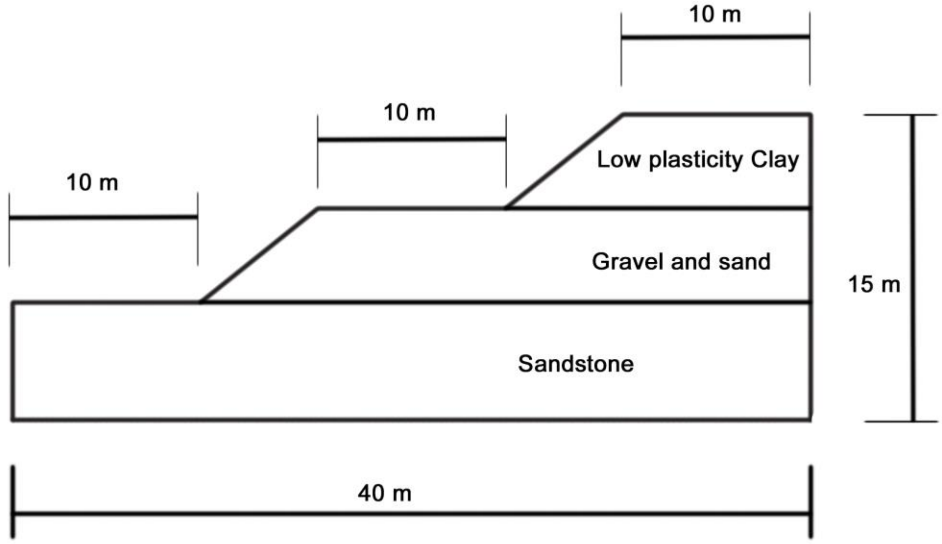


Fig. 4.1 Model slope used in the project

The material used in modelling are:

- The bottom layer is sandstone with following properties

  Density = 2700 kg/m^3

  Cohesion = 2.7×10^7 Pa

  Tension = 1.2×10^6 Pa

  Frictional angle = 27.8°

- The upper two layers are low plasticity clay and mixture of gravel and sand respectively from top and bottom. The properties are as follows:

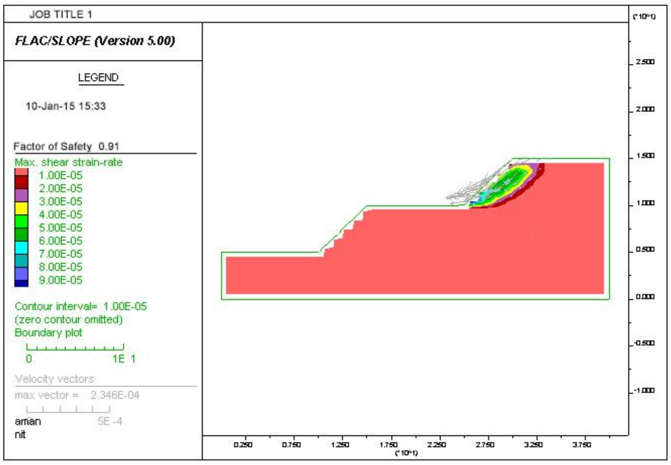
  Low plasticity clay

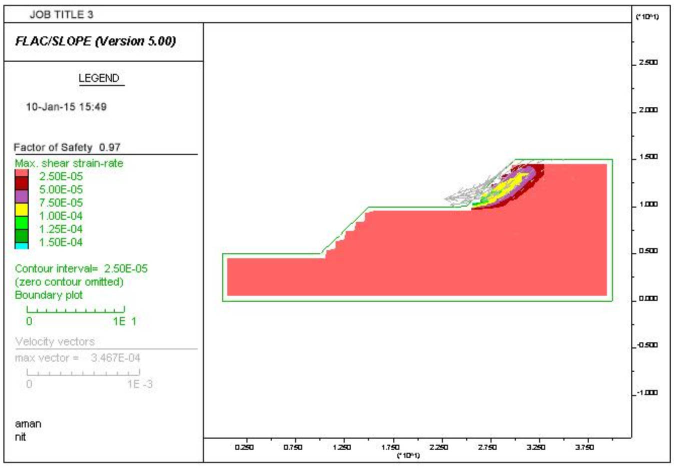
  Density = 1900 kg/m^3
  Cohesion = varied
  Friction = varied

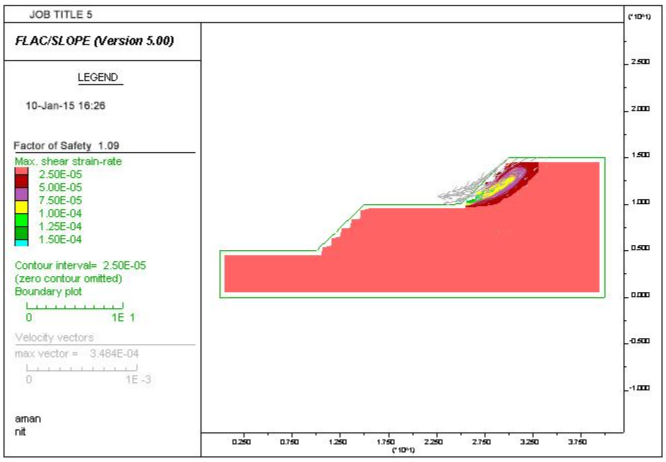
Gravel and Sand

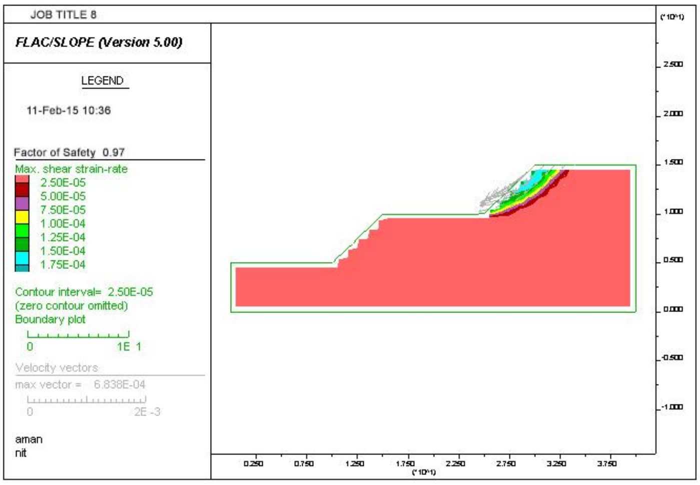
Density = 2000 kg/m^3
Cohesion = 5000 Pa
Friction = 38°

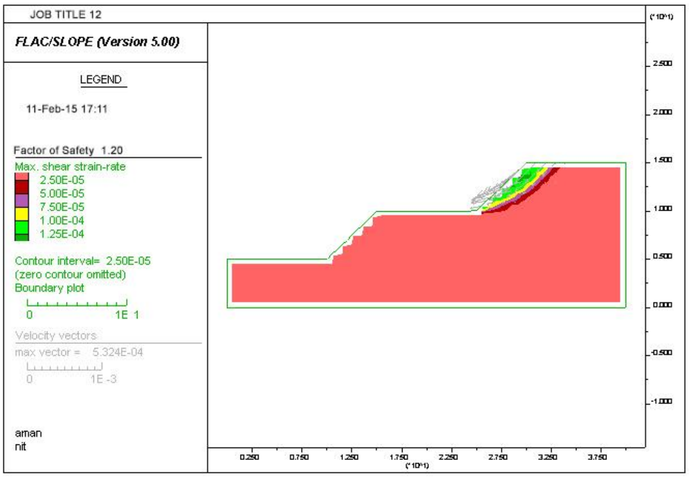
Some of the experimental results from FLAC are given below.

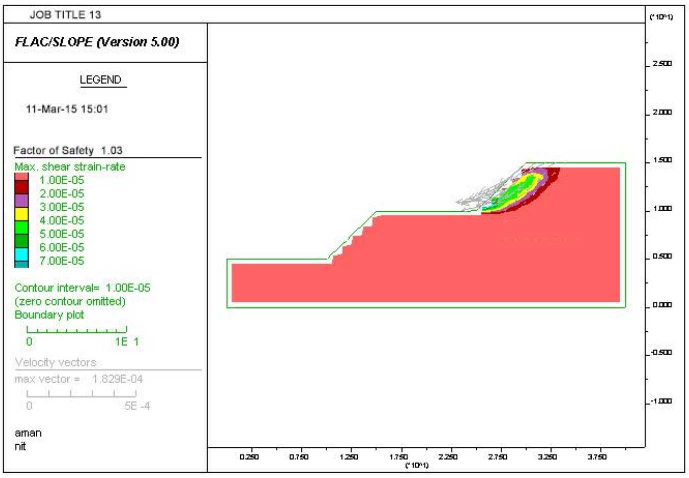












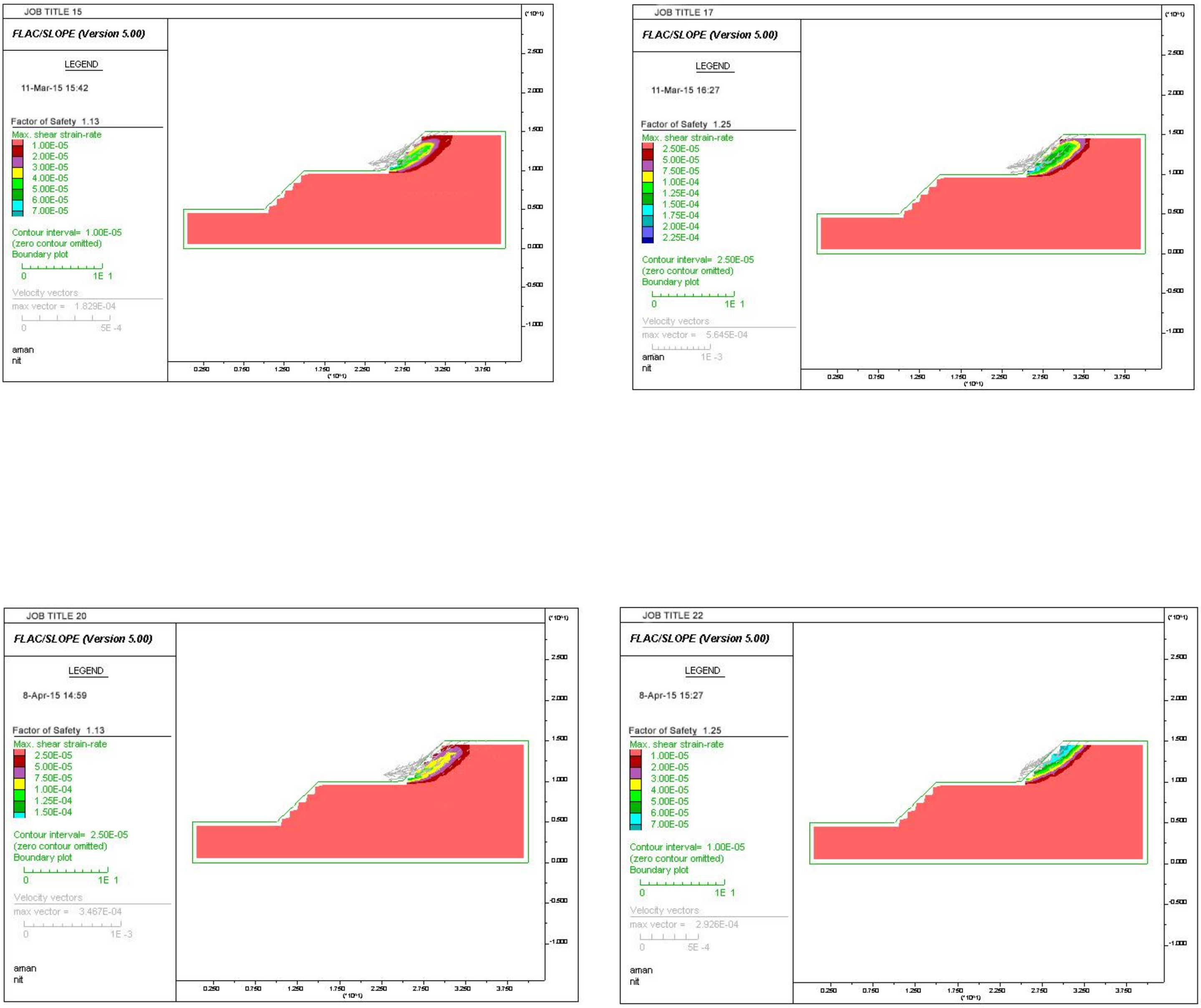


Fig. 4.2 FLAC models of some numerical models

The various experiments conducted and the results are as follows:

Cohesion value of top layer	**Friction angle of top layer**	**Factor of Safety**
6000 Pa	20°	0.91
	22°	0.92
	24°	0.97
	26°	1.03
	28°	1.09
	30°	1.21
8000 Pa	20°	0.92
	22°	0.97
	24°	1.03
	26°	1.08
	28°	1.14
	30°	1.20
10000 Pa	20°	1.03
	22°	1.08
	24°	1.13
	26°	1.19
	28°	1.25
	30°	1.31
12000 Pa	20°	1.12
	22°	1.13
	24°	1.19
	26°	1.25
	28°	1.31
	30°	1.44

Table 4.1 Experimental Results

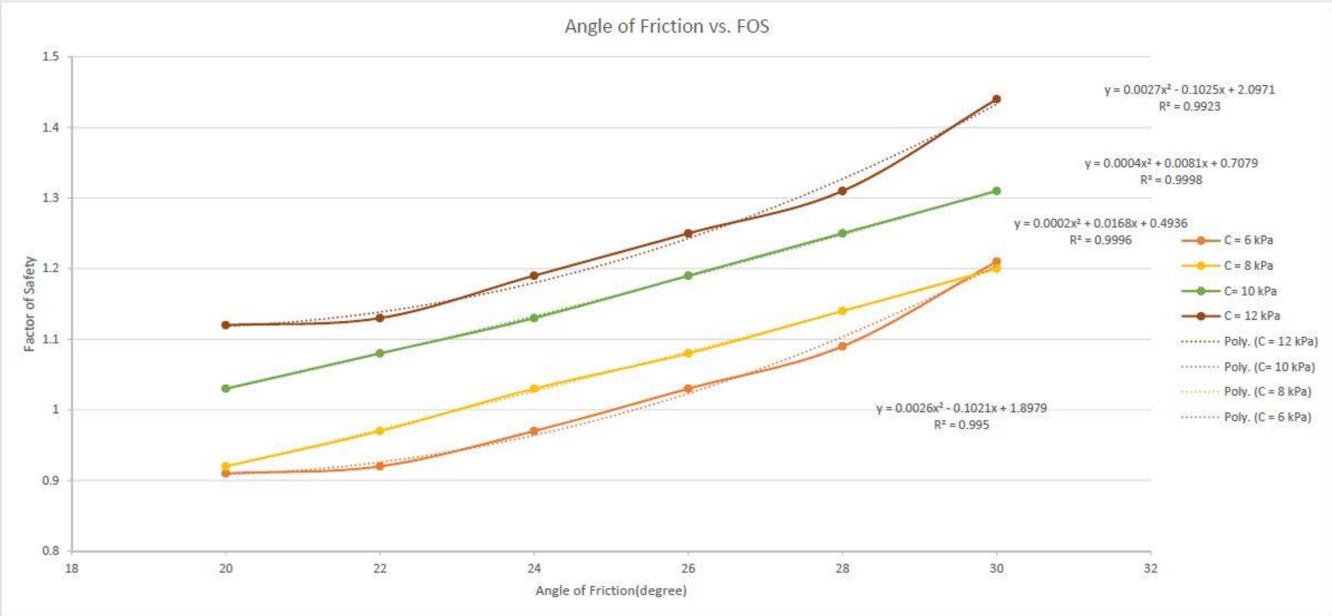


Fig. 4.3 Angle of friction vs. FOS

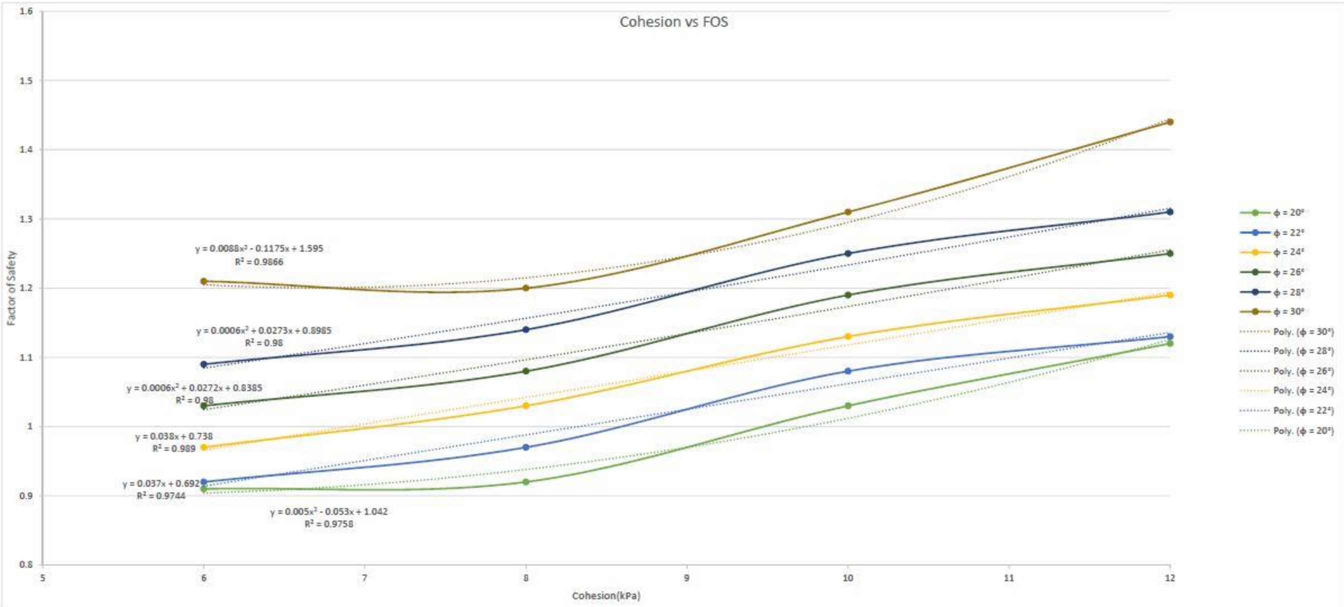


Fig. 4.4 Cohesion vs. FOS

Chapter 5
RESULTS AND CONCLUSIONS

5.1 Results

- Based on Table 4.6 it is concluded that as the cohesion and angle of internal friction increases, the factor of safety increases. As the cohesion increases, the binding property enhances which makes the slopes stable. High water content can weaken cohesion because abundant water both lubricates and adds weight to a mass. Moreover alternating expansion by wetting and contraction by drying of water reduces strength of cohesion.
- While running the numerical model FLAC/Slope it was observed that factor of safety changes with change in the resolution of the numerical mesh (coarse, medium and fine). In case of coarse mesh the factor of safety is quite approximate, while in fine mesh the factor of safety converges to the nearest possible value making it more accurate. However, calculation in coarse mesh is faster than in fine mesh. So depending upon the requirement and time availability of modeller, the mesh has to be selected.

5.2 Conclusion

Opencast mining is a very cost-effective mining method allowing a high grade of mechanization and large production volumes. Mining depths in open pits have increased steadily during the last decade which has the increased risk of large scale stability problems. It is necessary to assess the different types of slope failure and take cost effective suitable measures to prevent, eliminate and minimize risk.

The different types of the slope stability analysis techniques and software are available for slope design. Numerical modelling is a very versatile tool and enables us to simulate failure behavior and deforming materials. FLAC/Slope is user friendly software which is operated entirely from FLAC's graphical interface (the GIIC) and provides for rapid creation of models for soil/rock slopes and solution of their stability condition. Moreover it has advantages over a limit equilibrium solution like any failure mode develops naturally; there is no need to specify a range of trial surfaces in advance and multiple failure surfaces (or complex internal yielding) evolve naturally, if the conditions give rise to them. In this project, an attempt has been made to get acquaintance with the powerful features of FLAC/Slope in analysis and design of stable slopes in opencast mines.

The parametric study which was carried by varying the cohesion, angle of internal friction and ultimate slope angle showed that with increase in ultimate slope angle, the factor of safety decreases. Moreover cohesion and angle of internal friction are quite important factors affecting slope stability. With increase in both the parameters the stability increases. Conduct of slope stability assessment in Indian mines is mostly based on empirical and observational approach; hence effort is made by statutory bodies to have more application of analytical numerical modelling in this field to make slope assessment and design scientific. This will ensure that suitable corrective actions can be taken in a timely manner to minimize the slope failures and the associated risks.

5.3 Scope for future work

For the parametric studies, only cohesion and friction angle have been considered. However this study can be reached out to individual bench angles where all the benches may not be of same height. The conditions assumed during this analysis are such that there is no effect of water table and geological disturbances. Along with cohesion and friction angle other parameters like effect of geological disturbances, water table and blasting can be carried out. For slope stability analysis other numerical models such as UDEC and Galena can also be used in order to compare the sensitivity and utility of the different software.

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